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Yield monitoring to evaluate nitrogen management practices for corn

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Yield monitoring to evaluate nitrogen management practices for corn

by

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This is to certify that the master's thesis of

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Signatures have been redacted for privacy

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ABSTRACT

Soil and cornstalk testing has been used to evaluate nitrogen (N) management practices used during corn (*Zea mays* L.) production, but there is need to search for more practical methods. New yield monitoring technologies are rapidly being accepted by producers and offer an alternative method to evaluate N management practices. The objective of this thesis was to explore the potential and limitations of applying extra N in reference strips during the growing season and measure yield responses to evaluate the performance of N management practices used by producers who apply all N before or at planting. Field studies were conducted at 66 sites where extra (i.e., in addition to that normally applied by producers) fertilizer N was applied in replicated strips going the length of the field and yield increases were measured by using yield-monitoring combines. The late-spring test for soil nitrate and the end-of-season test for stalk nitrate were used to help explain why yield increases were, or were not, observed. Amounts of spring rainfall indicated that losses of N were near long-term means. Mean yield increases to the extra fertilizer N were not great enough to justify the expense of the fertilizer and application. This finding indicates that application of extra N is not likely to be profitable unless responsive sites can be predicted before fertilization. The soil and stalk tests showed agreement that some sites were deficient of N even though yield increases to the extra N were not observed. This finding suggests that the extra fertilizer N did not become available to the plants at some sites. This observation offers a new explanation for why the soil test often does not accurately predict yield responses to applied N and suggests that simultaneous use of soil nitrate testing in

late spring, cornstalk testing at the end of the season, and measuring yield responses to N applied in strips during the growing season may help identify in-season fertilizer practices that are most efficient.

INTRODUCTION

Recent studies have shown that soil testing for nitrate in late spring and cornstalk testing for nitrate at the end of the season can be used to evaluate N management practices used during corn production (El-Hout and Blackmer, 1990; Balkcom et al., 2003; Hanson et al., 2004). These tests have been calibrated to indicate the sufficiency of N for plant growth (Blackmer et al., 1989; Binford et al., 1990; Binford et al., 1992a, 1992b), where sufficiency of N for corn growth refers to the N supply relative to the crop needs (Blackmer, 2000; Balkcom et al., 2003). The sufficiency of N is described on numerical scales (i.e., test results) that range from below optimal to above optimal. The tests are diagnostic tools that use relationships observed in the past to estimate the sufficiency of N at any site where samples are collected.

As noted by Balkcom et al. (2003), soil testing after fertilization evaluates an outcome of N management (i.e., sufficiency of N when plants start rapid growth) and can detect problems associated with N losses soon after fertilization. Such testing, therefore, needs to be clearly distinguished from soil testing before fertilization, which is done to estimate the amount of fertilizer that should be applied. It is noteworthy that interest in soil nitrate testing in Iowa originated from evidence that substantial amounts of the fertilizer N applied in the fall or early spring (i.e., the normal application times in Iowa) are often lost from the surface layer before plants are 15 cm tall (Blackmer et al., 1989).

The cornstalk test for nitrate evaluates the sufficiency of N at the end of the growing season, which is an important management outcome (Blackmer and

Mallarino, 1996; Balkcom et al., 2003). Like yield response measurements at the end of the season, cornstalk nitrate concentrations are influenced by all the important factors occurring during the season. Results of the cornstalk test are more useful when evaluating N management practices because the effects of N are separated from other factors that influence final yields. Because this test is taken at the end of the growing season, it evaluates fertilization practices for their ability to supply optimal amounts of N for plant growth late in the growing season.

Balkcom et al. (2003) studied relationships among early season (March through May) rainfall, soil test values in late spring, cornstalk test values at the end of the season, and nitrate concentrations in nearby rivers and found compelling evidence that early-season losses of nitrate from soils are an important factor affecting N supplies for plant growth and nitrate concentrations in rivers. Hansen et al. (2004) studied relationships among amounts of manure N applied in early spring, concentration of soil nitrate in late spring, and yield responses to fertilizer N applied after soil testing at 205 sites and found lack of consistent effects of the manure due to losses or immobilization of manure N before the corn started rapid growth. As pointed out by Hansen et al. (2004), soil testing for nitrate after application of animal manure measures the net effects of all processes that influence supplies of N before this time and helps to explain why yield responses to the fertilizer were, or were not, observed. Measurement of yield response to added fertilizer, of course, is a commonly used method for estimating the sufficiency of N for corn growth and the soil and stalk tests are calibrated in studies where such measurements are also made.

An important limitation of using soil and cornstalk testing to evaluate N management is that sample collection requires considerable time and sample analyses are expensive. Many producers are reluctant to rely on these tests because they are concerned about the reliability of the tests. A key question is the ability of a few samples to address spatial variability within their fields (Schroder et al., 2000).

Yield monitoring combines offer a potentially easier and more direct method of evaluating N management practices when used with "reference strips" applied in corn fields. The basic idea is that corn producers can use their equipment to apply a few strips of extra N in their fields and learn the extent to which yields are increased by this N. This method is more direct because producers can measure yield responses for themselves and estimate the economic benefits of applying the extra N. For producers who already have yield monitors, this method may be easier and less costly than soil and tissue sampling and analysis. The practice of applying extra N to provide reference strips has been recommended for use with chlorophyll meters and aerial photography (Peterson et al., 1993; Scharf and Lory, 2002). Application of N in strips also has been used to demonstrate large losses of N following fall applications of anhydrous ammonia (Blackmer, 1997; White and Blackmer, 1997; Lane, 2000). This technique, however, has not been rigorously evaluated for ability to assess N sufficiency levels in corn.

The objective of this thesis was to explore the potential and limitations of applying extra N in reference strips during the growing season and measure yield responses to evaluate the performance of N management practices used by producers who apply all N before or at planting. The late-spring test for soil nitrate and the end-of-season test for cornstalk nitrate were used to help explain why yield responses were, or were not, observed and to assess the possible benefits of using these tests in conjunction with the measurements of yield response.

All analyses were done with the assumption that the number of sites and years included in the study were great enough to explore the potential and limitations of the methods used even though too few sites and years were studied to give meaningful evaluation of specific management practices. Within field variability is important but will be discussed extensively in later publications.

MATERIALS AND METHODS

Studies were conducted at 66 experimental sites within the Clarion-Nicollet-Webster, Canisteo-Webster-Nicollet, and Canisteo-Clarion-Nicollet soil associations of central Iowa in the years 2001, 2002, and 2003. The landscape of this area is flat to gently rolling, divided into fields (usually 400 by 800 m) for management, and dominated by a corn-soybean cropping system. Major soil series in the sites studied were Canisteo (fine-loamy, mixed (calcareous), mesic Typic Haplaquolls), Clarion (fine-loamy, mixed, mesic Typic Hapludolls), Nicollet (fine-loamy, mixed, mesic Aquic Hapludolls), Webster (fine-loamy, mixed, mesic Typic Haplaquolls), and Harps (fine-loamy, mesic Typic Calciaquolls). The soil associations and major soil map units for each site are shown in Tables 1 and 2.

The experimental sites were located within larger fields managed by producers using their normal practices. Sites were planted with 12 to 24 row equipment and rows were 76 cm apart. All sites received normal application of N as fertilizer or manure. Rates of N application are shown in Tables 3 and 4. Tillage practices are also shown in Tables 3 and 4. Minimum-tillage fields will be considered fields where no-till, ridge-till, or strip-till was practiced. All other tillage practices will be noted as conservation tillage.

Two fertilizer treatments were included in the study. The first was the rate applied by the producer. The second was the rate applied by the producer plus an additional 56 to 112 kg N ha^{-1} applied either in June or after June. The June application was made between the time the corn plants were 30 cm tall and the end of June. For the application after June, the fertilizer was applied near tasseling.

Table 1. Demographic information for sites with application in June.

Site	County	Association	Soil Map Units (% of total area) [1]	Area
				- ha -
1	Greene	Clarion-Nicollet-Webster	507 (54), 6 (14), 138 (10), 638 (9)	7.2
2	Howard	Cresco-Clyde-Protivin	84 (87), 798 (13)	1.5
3	Greene	Clarion-Nicollet-Webster	507 (71), 6 (18), 236 (7), 138 (4)	3.0
4	Greene	Canisteo-Webster-Nicollet	55 (48), 878 (22), 138 (11), 879 (10)	5.9
5	Boone	Canisteo-Clarion-Nicollet	507 (28), 138 (26), 95 (23), 55 (13)	5.6
6	Greene	Canisteo-Webster-Nicollet	55 (26), 507 (19), 95 (16), 4 (13)	9.7
7	Boone	Canisteo-Clarion-Nicollet	138 (30), 507 (16), 308 (12), 95 (12)	10.6
8	Greene	Canisteo-Webster-Nicollet	507 (68), 55 (27), 6 (5)	4.9
9	Buchanan	Readlyn-Tripoli-Oran	171 (51), 471 (41), 391 (7)	5.1
10	Story	Clarion-Webster-Nicollet	138 (63), 507 (21), 55 (10), 107 (5)	3.7
11	Blackhawk	Readlyn-Tripoli	399 (38), 83 (29), 398 (23), 776 (9)	12.5
12	Boone	Canisteo-Clarion-Nicollet	55 (32), 138 (31), 507 (22), 107 (15)	7.5
13	Story	Clarion-Webster-Nicollet	95 (58), 107 (36), 55 (6)	3.2
14	Greene	Clarion-Coland-Storden	107 (48), 138 (43), 55 (9)	5.1
15	Kossuth	Nicollet-Canisteo-Webster	55 (58), 107 (22), 138 (13), 507 (8)	6.2
16	Greene	Canisteo-Webster-Nicollet	107 (35), 507 (32), 4 (15), 55 (11)	8.1
17	Hamilton	Canisteo-Clarion-Nicollet	138 (45), 507 (31), 107 (14), 55 (10)	6.0
18	Greene	Canisteo-Webster-Nicollet	138 (64), 55 (18), 107 (16), 507 (2)	5.9
19	Boone	Canisteo-Clarion-Nicollet	507 (77), 90 (8), 55 (7), 95 (7)	7.7
20	Cherokee	Marcus-Primghar-Galva	92 (48), 310 (37), 91 (15)	5.1
21	Greene	Canisteo-Webster-Nicollet	107 (45), 55 (23), 138 (14), 878 (11)	6.7
22	Boone	Canisteo-Clarion-Nicollet	138 (59), 107 (29), 55 (9), 62 (3)	8.4
23	Greene	Canisteo-Webster-Nicollet	107 (46), 507 (25), 55 (23), 6 (4)	7.8
24	Greene	Lester-Fluvaquents-Wadena	236 (48), 386 (38), 34 (14)	3.3
25	Boone	Canisteo-Clarion-Nicollet	507 (39), 95 (23), 138 (18), 55 (17)	8.4
26	Story	Clarion-Webster-Nicollet	138 (69), 107 (25), 55 (6)	7.9
27	Boone	Canisteo-Clarion-Nicollet	138 (43), 507 (40), 95 (14), 55 (2)	6.1
28	Boone	Canisteo-Clarion-Nicollet	507 (51), 138 (27), 55 (18), 107 (4)	6.2
29	Boone	Canisteo-Clarion-Nicollet	507 (70), 55 (14), 138 (10), 95 (6)	9.9
30	Boone	Canisteo-Clarion-Nicollet	507 (37), 107 (30), 55 (25), 138 (7)	8.2
31	Boone	Canisteo-Clarion-Nicollet	138 (39), 55 (22), 107 (16), 507 (12)	9.5
32	Boone	Canisteo-Clarion-Nicollet	95 (56), 507 (26), 55 (10), 138 (7)	7.7
33	Boone	Canisteo-Clarion-Nicollet	55 (43), 138 (23), 507 (18), 107 (8)	7.2
34	Boone	Canisteo-Clarion-Nicollet	138 (42), 107 (28), 55 (21), 62 (7)	8.5

[1] 4, Knoke; 6, Okoboji; 34, Esterville; 55, Nicollet; 62, Storden; 83, Kenyon; 84, Clyde; 90, Okoboji; 91, Primghar; 92, Marcus; 95, Harps; 107, Webster; 138, Clarion; 171, Bassett; 236, Lester; 259, Biscay; 308, Wadena; 310, Galva; 325, Le Sueur; 386, Cordova; 391, Clyde-Floyd complex; 398, Tripoli; 399, Readlyn; 471, Oran; 507, Canisteo; 585; Coland-Spillville complex; 638, Clarion-Stroden complex; 655, Crippin; 776, Lilah; 798, Protivin; 878, Ocheyedan; 879, Fostoria; 1135, Coland

Table 2. Demographic information for sites with application after June.

Site	County	Association	Soil Map Units (% of total area)	Area
				- ha -
1	Greene	Clarion-Nicollet-Webster	507 (48), 107 (30), 138 (14), 6 (8)	7.4
2	Greene	Lester-Fluvaquents-Wadena	138 (33), 55 (24), 386 (19), 325 (17)	4.7
3	Boone	Canisteo-Clarion-Nicollet	107 (45), 138 (29), 55 (25), 62 (1)	5.7
4	Greene	Canisteo-Webster-Nicollet	507 (47), 95 (17), 4 (13), 55 (11)	9.7
5	Greene	Clarion-Nicollet-Webster	507 (84), 6 (13), 236 (3)	1.9
6	Greene	Canisteo-Webster-Nicollet	107 (69), 6 (15), 55 (8), 878 (4)	5.7
7	Boone	Canisteo-Clarion-Nicollet	107 (36), 55 (22), 138 (20), 585 (12)	9.4
8	Greene	Clarion-Coland-Storden	55 (46), 138 (35), 107 (19)	5.0
9	Story	Clarion-Webster-Nicollet	107 (47), 95 (44), 55 (9)	2.4
10	Boone	Canisteo-Clarion-Nicollet	107 (48), 55 (26), 138 (26)	2.3
11	Story	Clarion-Webster-Nicollet	138 (49), 107 (37), 55 (13)	6.3
12	Greene	Canisteo-Webster-Nicollet	107 (39), 55 (20), 138 (15), 507 (12)	14.2
13	Greene	Canisteo-Webster-Nicollet	55 (34), 138 (34), 507 (19), 107 (6)	7.1
14	Greene	Canisteo-Webster-Nicollet	107 (32), 55 (31), 507 (27), 6 (5)	6.6
15	Boone	Canisteo-Clarion-Nicollet	507 (69), 55 (16), 138 (15)	5.0
16	Boone	Coland-Talcot-Wadena	507 (36), 138 (36), 55 (10), 6 (8)	33.7
17	Boone	Canisteo-Clarion-Nicollet	95 (31), 507 (29), 138 (29), 655 (10)	4.6
18	Hamilton	Canisteo-Clarion-Nicollet	507 (40), 138 (32), 828 (24), 107 (5)	5.2
19	Boone	Canisteo-Clarion-Nicollet	507 (49), 138 (24), 55 (18), 6 (6)	9.9
20	Boone	Canisteo-Clarion-Nicollet	138 (36), 55 (22), 95 (22), 107 (14)	9.5
21	Boone	Canisteo-Clarion-Nicollet	507 (60), 138 (17), 55 (14), 95 (6)	31.1
22	Greene	Mayer-Biscay-Coland	259 (52), 34 (34), 108 (10), 308 (2)	5.4
23	Boone	Canisteo-Clarion-Nicollet	55 (63), 138 (26), 507 (7), 107 (5)	7.4
24	Greene	Canisteo-Webster-Nicollet	507 (53), 878 (21), 6 (19), 55 (4)	7.3
25	Boone	Canisteo-Clarion-Nicollet	138 (52), 507 (39), 55 (5), 107 (4)	9.8
26	Boone	Canisteo-Clarion-Nicollet	138 (27), 55 (20), 507 (20), 1135 (12)	8.5
27	Greene	Canisteo-Webster-Nicollet	138 (46), 55 (31), 507 (18), 107 (5)	13.0
28	Boone	Canisteo-Clarion-Nicollet	138 (33), 507 (32), 55 (13), 95 (12)	10.6
29	Boone	Canisteo-Clarion-Nicollet	507 (43), 90 (19), 655 (18), 95 (12)	21.4
30	Greene	Clarion-Nicollet-Webster	138 (68), 107 (22), 55 (10)	6.3
31	Boone	Canisteo-Clarion-Nicollet	138 (43), 507 (39), 55 (12), 107 (5)	7.7
32	Boone	Canisteo-Clarion-Nicollet	507 (44), 138 (44), 55 (9), 6 (2)	7.6

Table 3. Management information for sites with application in June.

Site	Year	Tillage[1]	Timing[2]	N Rate Base	N Rate Additional	Number of replicates
				------ kg N ha^{-1} ------		
1	2002	Min	F	157	84	6
2	2002	Cons	F	135	67	4
3	2001	Cons	S	157	112	5
4	2002	Cons	F-M	132	84	6
5	2002	Cons	F	168	84	6
6	2002	Cons	F	178	84	6
7	2002	Cons	F	210	84	6
8	2002	Min	F	157	84	4
9	2002	Cons	F	146	67	5
10	2001	Cons	F	169	56	5
11	2002	Min	F	137	73	5
12	2002	Cons	F	168	84	6
13	2001	Cons	F	169	56	5
14	2002	Cons	F	202	84	6
15	2002	Cons	F	155	56	5
16	2001	Cons	F	185	112	5
17	2002	Min	F	232	84	6
18	2002	Min	F	157	84	5
19	2001	Cons	F&S	179	112	5
20	2002	Cons	F	135	56	5
21	2002	Cons	F-M	132	84	6
22	2001	Min	F	193	56	5
23	2001	Cons	F	185	56	5
24	2001	Min	S	132	112	6
25	2001	Min	F	119	56	5
26	2001	Cons	F-M	145	112	5
27	2002	Cons	F	168	84	5
28	2001	Cons	F	135	56	5
29	2002	Min	F	191	84	6
30	2001	Cons	F	168	56	5
31	2002	Cons	F-M	211	84	6
32	2002	Cons	F	212	84	6
33	2002	Min	F	146	84	6
34	2002	Cons	F	236	84	6
Mean				168	79	

[1] Min – Minimum tillage
Cons – Conservation tillage

[2] F - Fall
S - Spring
M - Manure

Table 4. Management information for sites with application after June.

Site	Year	Tillage[1]	Timing[2]	N Rate Base	N Rate Additional	Number of replicates
				------ kg N ha^{-1} ------		
1	2002	Min	F	157	84	6
2	2001	Min	S	132	112	9
3	2002	Cons	F	235	84	6
4	2002	Cons	F	178	84	6
5	2003	Cons	S	135	84	4
6	2002	Cons	F-M	132	84	6
7	2003	Cons	F-M	231	84	6
8	2002	Cons	F	202	84	6
9	2003	Cons	F	203	84	4
10	2003	Min	F	163	84	4
11	2003	Cons	F	236	84	4
12	2001	Cons	F	185	56	9
13	2002	Min	F	157	84	6
14	2002	Cons	F-M	132	84	6
15	2003	Cons	F	156	84	4
16	2001	Cons	S	140	56	20
17	2002	Cons	F	168	84	5
18	2002	Min	F	232	84	6
19	2002	Min	F	191	84	6
20	2002	Cons	F-M	211	84	6
21	2001	Cons	S	140	56	9
22	2003	Cons	S	177	84	4
23	2002	Cons	F	168	84	6
24	2002	Min	F	157	84	6
25	2002	Min	F	146	84	6
26	2002	Cons	F	210	84	6
27	2001	Min	S	135	56	10
28	2003	Cons	F	154	84	4
29	2001	Cons	S	140	56	5
30	2003	Cons	S	219	84	4
31	2002	Cons	F	212	84	6
32	2003	Cons	S	159	84	6
Mean				175	81	

[1] Min – Minimum tillage
Cons – Conservation tillage

[2] F - Fall
S - Spring
M - Manure

These treatments were applied in alternating strips, where each strip was two combine swaths wide (i.e., strips were 12 to 24 rows wide) as shown in Fig. 1. Each treatment was applied to 4 to 20 replicates as shown in Tables 3 and 4. The fertilizer was applied as urea-ammonium-nitrate solution by using a high clearance applicator (John Deere 4700 or 4710 sprayer) that was equipped with drop nozzles that dribbled the solution on the soil surface midway between every other row. The nozzles were maintained approximately 5 cm above the soil surface to avoid plant damage caused by the fertilizer burning leaves.

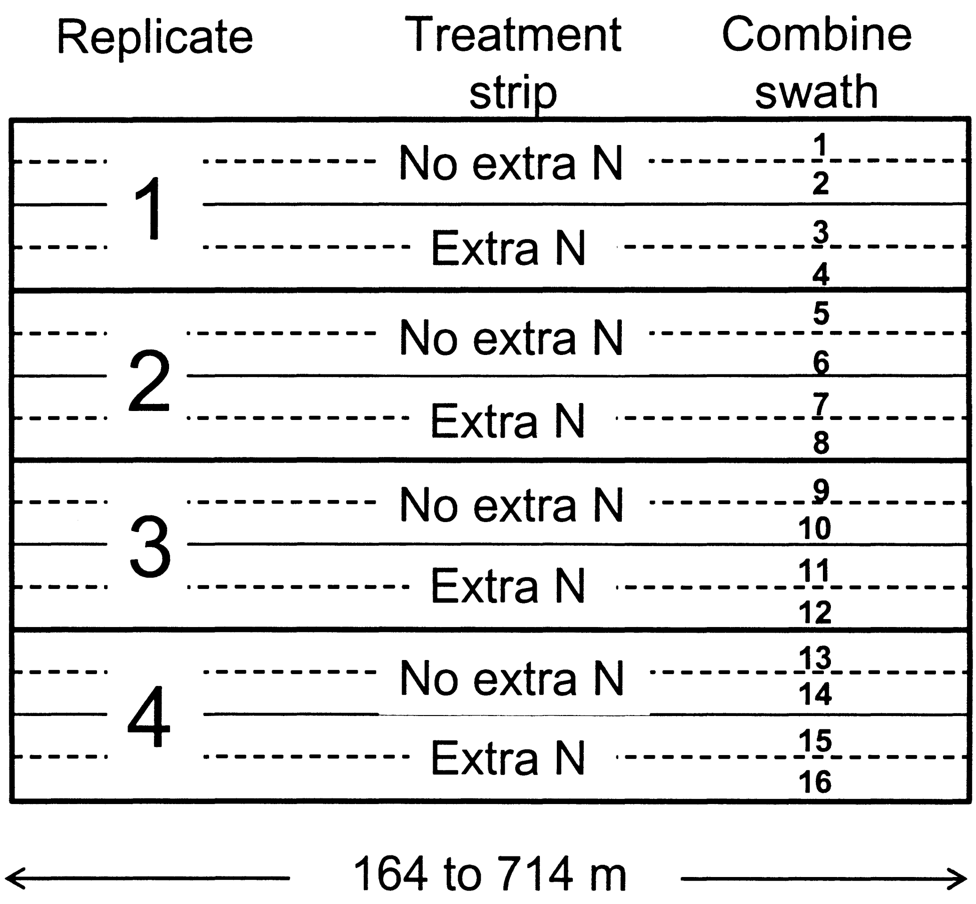

Fig. 1. Diagram of plot layout.

Each site was a rectangle (Fig. 1); the distance along rows for the June application ranged from 164 to 714 m (mean was 556 m), the distance across rows ranged from 77 to 216 m (mean was 124 m). The application after June had a range of 237 to 1464 m (mean was 624 m) for the distance along rows and a range of 73 to 487 m (mean was 144 m) for the distance across rows. The area for the June and after June application of each site ranged from 1.5 to 12.5 ha and from 1.9 to 33.7 ha with means of 6.8 and 9.1 ha as shown in Tables 1 and 2.

The strips were harvested using combines equipped with Ag Leader (Ag Leader, Ames, IA) or Green Star (Deere and Company, Moline, IL) yield monitors and differentially-corrected GPS using the coast guard signal. The yield monitors were calibrated by the producers and collected data at one-second intervals. The producers were instructed to maintain a constant combine speed to minimize problems associated with time lag. Because our sites were located within larger fields, the combines had established equilibrium flows before entering the study area and maintained this equilibrium through the entire area.

The yield monitor data collected by Ag Leader monitors were initially processed by using SMS Basic (Ag Leader, Ames, IA) and yield monitor data collected by Green Star monitors were initially processed by using JDOffice (Deere and Company, Moline, IL). The data were edited using ArcView (ESRI, Redlands, CA) for errors in position due to temporary loss of GPS signal, areas influenced by lack of plants or unusual situations (i.e., waterways planted to grass, areas where plants were drown by temporary flooding, etc.), and outliers were eliminated by deleting monitor readings of <1.88 Mg ha^{-1} and >25.08 Mg ha^{-1}. A grid was then imposed on the data to coincide with the treatment swaths by using an ArcView extension.

Mean yields for swaths were calculated from all the data points within a swath. Mean yields for strips were calculated from the means of the two swaths it contained. Strip means were used to calculate the site means for each treatment and Proc Mixed (SAS V8, SAS, Cary, NC) was used to evaluate the significance of the yield response to fertilizer N and to calculate LSD values.

Statewide monthly precipitation data for the past 30 years were obtained for sections 4 and 5 in Iowa from the National Climatic Data Center (2004). Information concerning nitrate loads in the Des Moines River at Des Moines was obtained from the Des Moines River Water Quality Network (DMRWQN) (Lutz, 2004). Load data from DMRWQN included both nitrate and nitrite, but is referred to as nitrate in this thesis.

Soil samples were collected to a 30-cm depth when corn plants were 15 to 30 cm tall in accordance with guidelines for using the test in Iowa (Blackmer et al., 1997). Thirty-two 1.7-cm-diameter cores were used to make a composite sample from a 0.2-ha area selected as relatively uniform and representative of a dominant soil map unit within the field at 5 locations within a site. The samples were dried (49°C) and ground to pass a 2-mm sieve. Nitrate N was determined by KCl extraction and steam distillation (Keeney and Nelson, 1982).

Cornstalk samples were collected by taking 15 20-cm segments of stalk beginning 15 cm above the ground 1 to 3 wk after physiological maturity in accordance with guidelines for using this test in Iowa (Blackmer and Mallarino, 1996). These 5 samples were taken at the same locations as the soil samples. The samples were dried at 60°C and ground to pass a 0.5-mm sieve. Samples of ground stalks were extracted with 1 *M* KCl and the extracts were analyzed for nitrate by using steam distillation (Keeney and Nelson, 1982).

RESULTS AND DISCUSSION

Characterization of Years

The amounts of rainfall that occurred during the period of March through May of the years studied were within the inter-quartile range of those observed in the same region for the past 30 years (Fig. 2). Annual means for loads of nitrate-N in the Des Moines River below the region studied were within the inter-quartile range of those observed during the past 30 years (Fig. 3). These observations suggest that the studies were conducted on years that were relatively near long-term means with respect to weather factors expected to influence losses of fertilizer N before crops grow. Although the data presented in Fig. 2 and 3 do not provide perfect characterization of years with respect to losses of fertilizer N before plants grow, observations by Balkcom et al. (2003) indicate that March through May rainfall and nitrate loads in rivers provide a reasonable way to classify years with respect to likelihood of fertilizer N losses before plants grow.

The results of this study could be considered reasonably typical of those expected in about one-half of the years likely to be encountered in the region studied. It must be clearly recognized, however, that the results may not be typical of those expected on years that fall within the highest quartile of years with respect to losses of fertilizer N before plants grow. Approximately one year in four should be expected to have greater losses of soil N and greater yield increases to extra N than were observed during this study. This observation is important because the economics of fertilization is such that profits from N fertilization are not normally distributed across years; relatively large profits from fertilization should be expected on years with unusually large losses of soil N and, therefore, the conclusions from such years would be markedly different than observed in this study. These observations illustrate the great importance of classifying years with respect to likelihood of losses of N when comparing data from different sites and years.

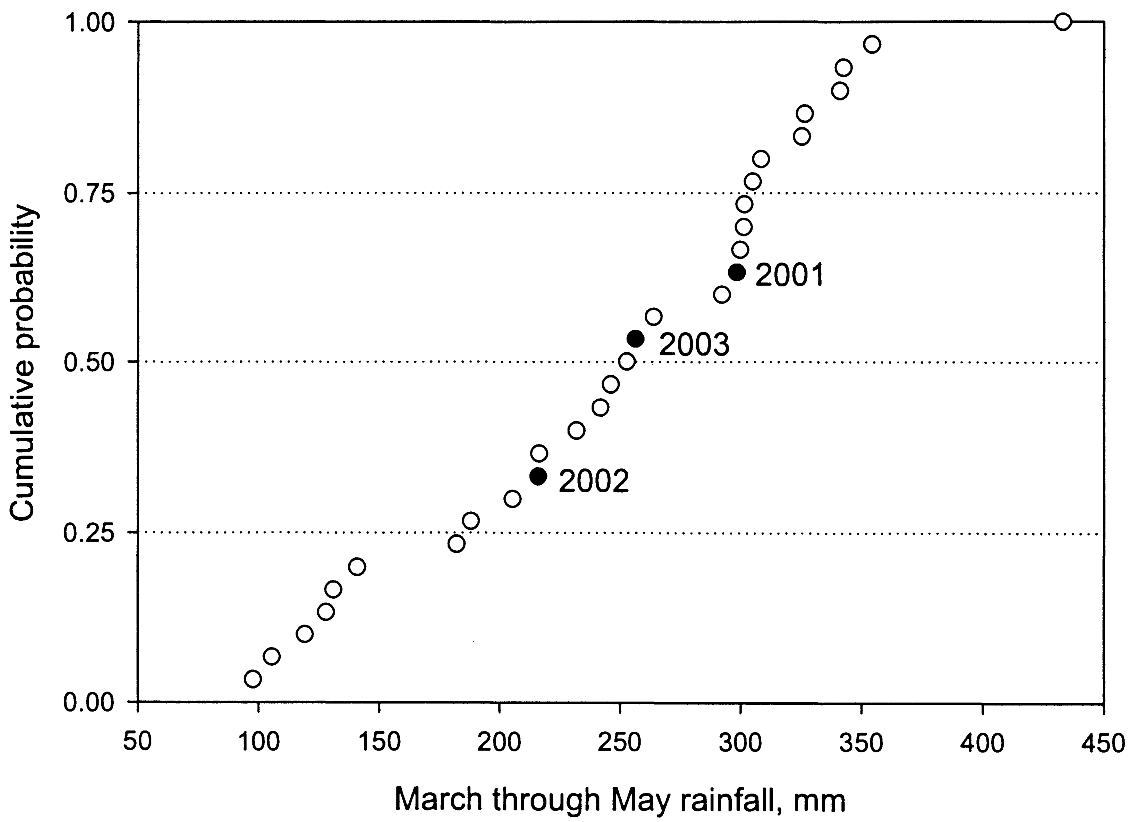

Fig. 2. Cumulative probability distribution for March through May rainfall for the past 30 years in the region of study.

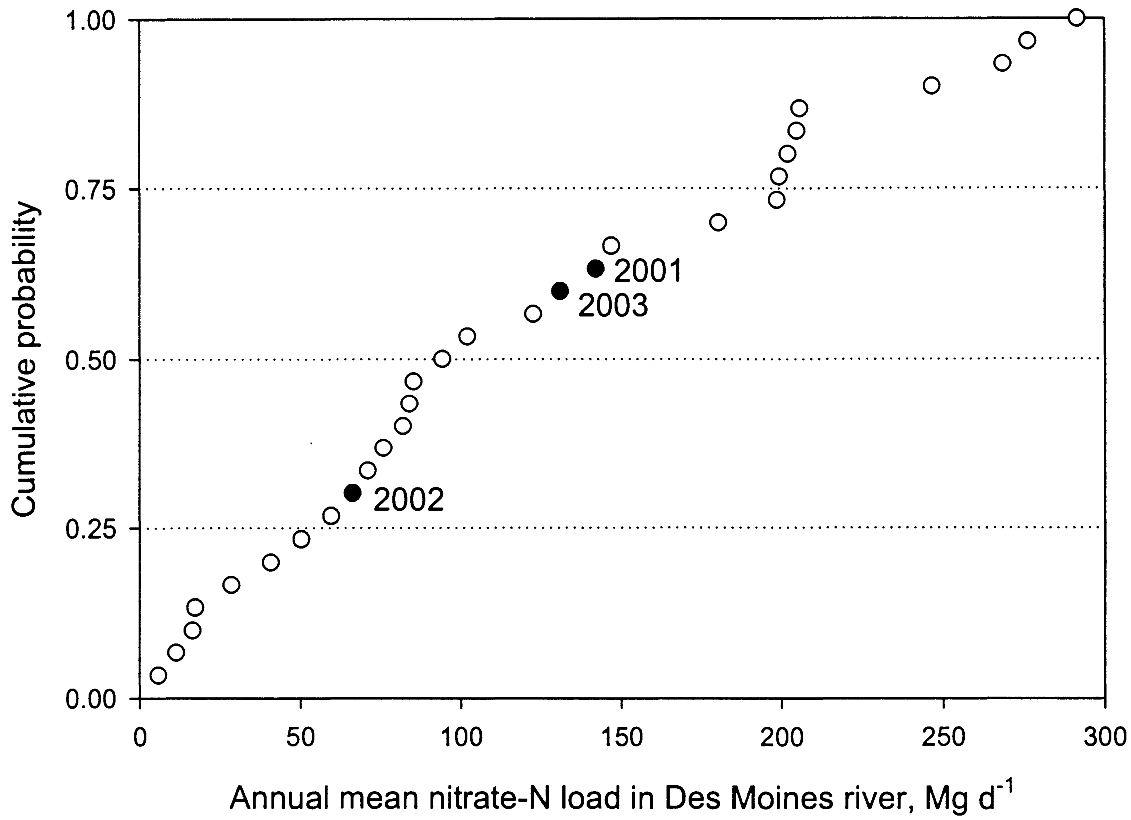

Fig. 3. Cumulative probability distribution for annual means of nitrate-N loads in the Des Moines river during the past 30 years.

Extra N Applied in June

Yield responses

The mean yields of corn grain at 34 sites were 11.13 Mg ha^{-1} without the extra N and 11.26 Mg ha^{-1} with the extra N applied in June (Table 5). Mean yield increase of 0.13 Mg ha^{-1} was too small to pay for the normal price for the additional

Table 5. Yields of corn grain with and without extra N applied in June.

Site	Yield With Extra N	Yield Without Extra N	Yield Increase	LSD	p-value
	Mg ha^{-1}				
1	12.53	11.42	1.11	0.75	0.01
2	12.08	11.47	0.61	0.52	0.03
3	11.94	11.47	0.47	0.45	0.05
4	11.32	10.93	0.39	0.12	0.00
5	12.58	12.28	0.30	0.19	0.01
6	13.11	12.84	0.27	0.14	0.00
7	12.25	12.00	0.24	0.36	0.15
8	12.51	12.27	0.24	0.33	0.11
9	13.41	13.21	0.21	0.13	0.01
10	11.39	11.22	0.17	0.08	0.00
11	13.14	12.96	0.17	0.13	0.01
12	9.72	9.57	0.15	0.12	0.02
13	11.36	11.21	0.15	0.35	0.36
14	13.07	12.92	0.15	0.24	0.18
15	12.22	12.07	0.15	0.23	0.15
16	10.96	10.86	0.10	0.20	0.23
17	10.51	10.41	0.10	0.15	0.15
18	12.34	12.24	0.10	0.24	0.32
19	10.72	10.63	0.08	0.47	0.65
20	11.50	11.43	0.07	0.22	0.42
21	11.27	11.20	0.06	0.21	0.47
22	11.24	11.18	0.06	0.19	0.43
23	10.62	10.58	0.04	0.16	0.51
24	5.85	5.82	0.03	0.19	0.66
25	11.68	11.67	0.01	0.19	0.86
26	7.95	7.94	0.01	0.27	0.93
27	9.70	9.69	0.00	0.40	0.98
28	9.83	9.84	0.00	0.25	0.97
29	11.26	11.28	-0.02	0.25	0.85
30	11.16	11.25	-0.09	0.08	0.02
31	13.17	13.28	-0.11	0.12	0.07
32	11.24	11.37	-0.13	0.74	0.67
33	8.32	8.53	-0.22	0.53	0.38
34	11.03	11.31	-0.27	0.83	0.43
Mean	11.26	11.13	0.13		

fertilizer and application (i.e., >0.38 Mg ha^{-1}), so it must be concluded that it was not profitable to apply the extra N across all sites.

Yield increases resulting from the extra N at individual sites ranged from 1.11 to -0.27 Mg ha^{-1} and had a mean of 0.13 Mg ha^{-1}. The yield increases were large enough to pay for the fertilizer and application at 4 of the sites. Only at 1 site was the yield increase great enough to give a two-fold economic return to fertilization, so there were no extremely large returns to fertilization at any site. The finding that fertilization was profitable at only 4 of 34 sites suggests that, unless there is clear evidence for need of the extra N, it is not wise to apply extra fertilizer just because there is a chance that large returns may be attained.

The finding of relatively few yield increases to the extra N should not be considered evidence for lack of losses of fertilizer N applied by the producer. The mean rate of fertilizer applied by the producer was 168 kg N ha^{-1}. Recent studies (White and Blackmer, 1999; Van De Woestyne and Blackmer, 2002) show that 112 kg N ha^{-1} is adequate to maximize profits for corn after soybean if the fertilizer N is delayed (until after crops have emerged) to minimize losses associated with spring rainfall. Before a yield increase should be expected, therefore, loss of approximately one-third of the fertilizer N applied by the producer would have to occur. These observations are consistent with reports that producers normally apply extra N as insurance to prevent yield losses in years with above average losses of fertilizer N before plants grow (Scharf and Lory, 2002).

The mean rate applied by producers for corn after soybean (without manure) was 169 kg N ha^{-1} and the mean yield of grain was 11.17 Mg ha^{-1}. The rate applied by the producer, therefore, was 26 kg N ha^{-1} less than the amount recommended by using yield goals and credits for legumes (Fig. 4). Such recommendations, call for producers to apply 195 kg N ha^{-1} (11.17 Mg ha^{-1} times 21.45 – 44.83 kg ha^{-1}). The producers applied 169 kg N ha^{-1}. These observations suggest that the normal recommendations include extra N for insurance against yield losses in years with above normal N losses.

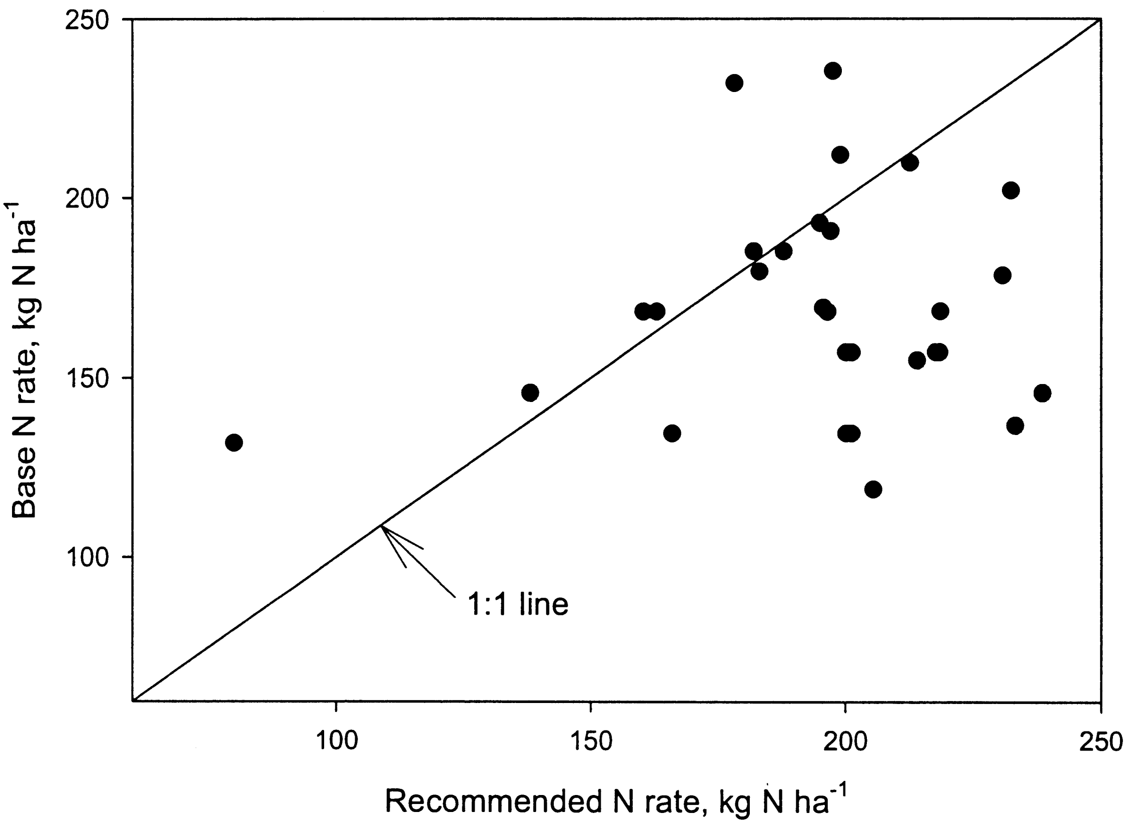

Fig. 4. Relationship between normally recommended N rates and rates of N applied by producers (at sites where N was applied in June).

Analysis of variance showed that yield responses were statistically significant ($p < 0.05$) at 11 of 34 sites (Table 5). Yield increases >0.25 Mg ha^{-1} were significant and yield increases <0.15 Mg ha^{-1} usually were not significant. Our ability to detect small yield responses is better than that normally expected in small plot trials because other studies have shown that yield responses <7% are usually not statistically significant due to unexplained spatial variability within and among plots (Blackmer, 1986; Piekielek et al., 1995; Fox et al., 2001).

The statistical significance of the yield increases within a field is unimportant in discussions elsewhere in this thesis because each field is considered to be a single observation and trends across fields are being studied. It should be noted that yield increases were measured on a high percentage of each field (rather than a small sample of that field) and, therefore, the yield increases measured should provide a good estimate of the profitability of fertilization. The statistical significance of measured yield increases is largely determined by amounts of variability within the field and how the strips were positioned relative to this variability. Because we made no effort to position the strips so as to minimize the variability among strips, the statistical significance is not a meaningful measure of the benefits of fertilization.

Soil nitrate concentrations

The relationship between soil nitrate concentrations measured in late spring and yield increases to the extra N is shown in Fig. 5 and values in Table 6. Soil nitrate concentrations in late spring are of interest because they can be used to estimate losses of N and likelihood of response to additional fertilizer (Blackmer et al., 1989; Hanson et al., 2004). Mean yield increases were 0.26 Mg ha^{-1} for sites testing <10 mg kg^{-1} and 0.05 Mg ha^{-1} for sites testing >10 mg kg^{-1}. Soil nitrate concentrations of 10 mg kg^{-1} have been described as the critical level that distinguishes sites with a higher probability of response to extra fertilizer after applications of anhydrous ammonia (Blackmer, 1998).

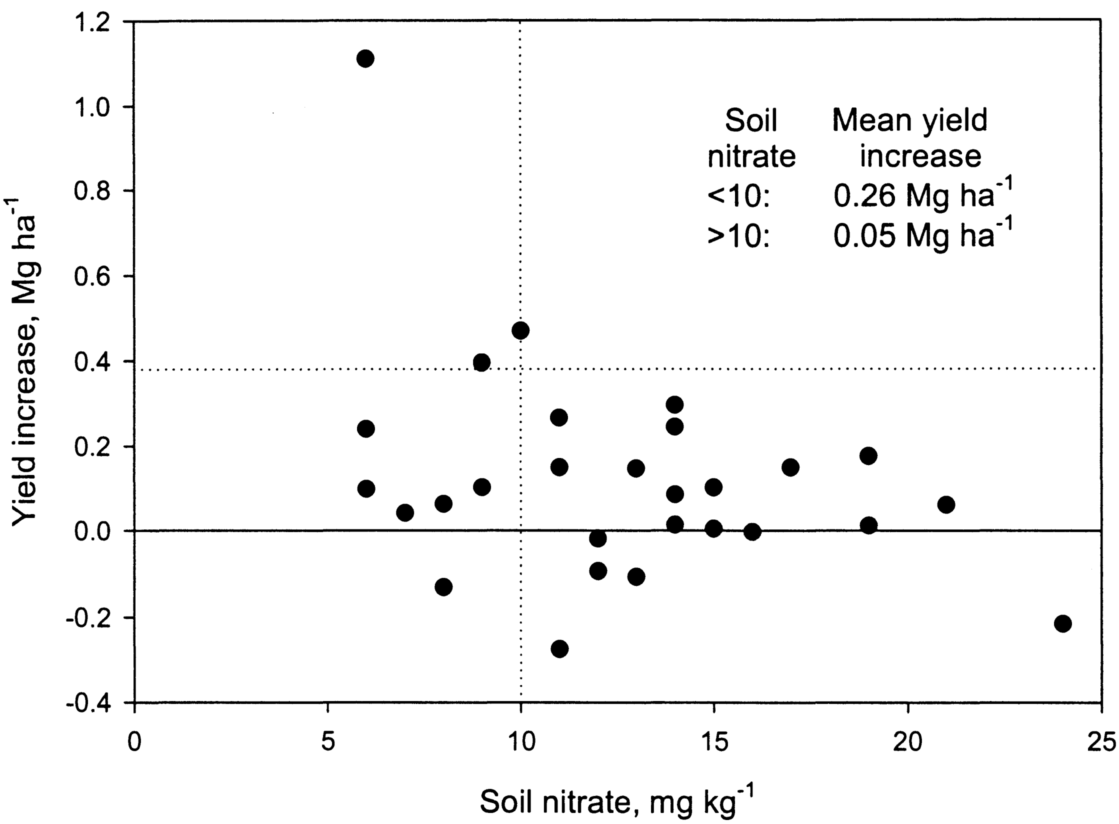

Fig. 5. Relationship between soil nitrate concentrations and yield increases to extra N applied in June.

Table 6. Soil and stalk nitrate concentrations for sites applied in June.

Site	Soil Nitrate		Stalk Nitrate			
			With Extra N		Without Extra N	
	Mean	Range	Mean	Range	Mean	Range
	mg N kg^{-1}		g N kg^{-1}			
1	6	3 - 9	0.9	0.5 - 1.3	0.3	0.2 - 0.5
2	--	----	--	----	--	----
3	10	7 - 13	0.7	0.1 - 2.4	0.2	0.0 - 0.8
4	9	6 - 13	0.3	0.0 - 0.6	0.1	0.0 - 0.2
5	14	5 - 28	0.4	0.1 – 1.0	0.5	0.0 - 1.1
6	11	8 - 15	0.5	0.1 - 0.9	0.2	0.0 - 0.4
7	14	8 - 19	2.4	1.8 - 2.8	1.4	0.0 - 2.5
8	6	4 - 10	0.5	0.4 – 1.0	0.1	0.0 - 0.3
9	--	----	--	----	--	----
10	19	12 - 23	2.7	1.3 - 5.7	3.2	1.2 - 5.4
11	--	----	--	----	--	----
12	11	7 - 15	1.1	0.8 - 1.4	1.0	0.7 - 1.3
13	17	10 - 33	2.5	1.4 - 2.9	1.0	0.1 - 1.9
14	13	6 - 19	0.1	0.1 - 0.2	0.2	0.0 - 0.5
15	--	----	--	----	----	----
16	9	5 - 12	1.8	0.8 - 2.9	0.7	0.3 - 1.3
17	15	13 - 18	0.8	0.3 - 1.6	0.3	0.1 - 0.5
18	6	4 - 10	1.5	0.4 - 3.7	0.8	0.0 - 1.5
19	14	9 - 18	1.4	0.3 - 2.4	1.2	0.2 - 2.7
20	--	----	--	----	----	----
21	8	4 - 12	0.2	0.2 - 0.3	0.1	0.0 - 0.2
22	21	16 - 24	6.4	3.3 - 7.6	5.5	2.3 - 7.1
23	7	5 - 8	1.9	0.6 - 3.3	1.1	0.1 - 1.4
24	--	----	0.7	0.4 - 1.1	0.2	0.1 - 0.4
25	14	7 - 21	4.4	4.1 – 5.0	2.2	1.0 - 3.7
26	19	16 - 30	3.2	0.1 - 4.6	2.8	0.9 - 3.6
27	15	9 - 21	1.0	0.7 - 1.5	1.5	0.5 - 2.8
28	16	11 - 23	5.9	3.0 - 7.4	6.1	5.5 - 7.5
29	12	9 - 14	0.9	0.7 - 1.2	0.6	0.4 - 0.8
30	12	9 - 14	2.5	0.0 - 5.8	2.3	0.0 - 4.2
31	13	8 - 21	0.5	0.2 - 0.8	0.8	0.5 - 1.1
32	8	5 - 12	0.5	0.2 – 1.0	0.1	0.1 - 0.2
33	24	16 - 32	0.5	0.3 - 0.6	0.2	0.1 - 0.3
34	11	7 - 16	0.9	0.6 - 1.2	0.5	0.0 - 0.8
Mean	14		1.4		1.0	

Although the lower testing sites tended to be more responsive than the higher testing sites, the mean yield increase for this class was not significant enough to justify the additional expenses of the fertilizer and application. It should be noted, however, that substantially greater yield increases could have been observed if more rainfall and subsequent losses of N had occurred. Large yield increases in wet years, for example, have been observed (Blackmer, 1997; White and Blackmer 1997; Lane, 2000). An important point illustrated by this study is that classification of years by likelihood of N losses can be used to identify when soil nitrate testing is not needed. In years where high N losses are likely, the soil test can be used to classify fields with respect to amounts of N loss that actually occurred. Classification by years first, however, greatly reduces the amount of soil testing needed and makes soil testing more practical.

It should be noted that the soil samples were collected at selected points within the overall area where yield increases to fertilizer N were measured. The ability of soil testing to predict yield increases, therefore, is dependent upon the ability to select points that represent the area, as well as the basic ability of the soil nitrate test to predict yield increases. There have been essentially no published studies to assess the magnitude of problems associated with sampling fields for soil nitrate concentrations.

Tillage

Figure 6 shows relationships among tillage practices, soil nitrate concentrations measured in late spring, and yield increases to the extra N. Tillage is of potential interest because producers know their tillage system and, therefore, fields can be classified by tillage system. Approximately one-third of the minimum-tillage fields had soil nitrate concentrations <10 mg kg^{-1}, and mean yield increases were great enough to justify application of the extra N. Only 30% of the conservation-tillage fields tested <10 mg kg^{-1} soil nitrate concentration, and the mean yield increases were not great enough to justify application of extra N. The results suggest possible benefits from distinguishing between the tillage systems. When this distinction is made, it was profitable to fertilize minimum-tillage fields that have soil nitrate concentrations <10 mg kg^{-1} even in normal years.

There are several possible reasons why minimum-tillage fields could be different than conservation-tillage fields. One is that higher residue cover on the minimum-tillage fields delays cooling of the soils in the fall, allowing more nitrification to occur in the fall and, therefore, increasing the opportunity for losses of N during spring rainfall (Kyveryga et al., 2004). A second possible reason is that greater residual cover tends to make the soils wetter in the spring and, therefore, increases the amount of water that moves through the soil profile during spring rainfall events (Thomas et al., 1973). A third possible reason is that the minimum-tillage fields have more macro pores and, therefore, greater preferential movement of water and nitrate through the soil profile (Priebe and Blackmer, 1989; Thomas et al., 1989). The exact reason cannot be determined from the data collected in this study. Because of the small number of minimum-tillage fields included in this study, additional sites need to be evaluated to confirm the usefulness of classifying fields by tillage practice. It is noteworthy that, large losses of fall applied N reported by

White and Blackmer (1997), Lane (2000), and Kyveryga et al. (2004) were observed on minimum-tillage soils. The results in this study, therefore, essentially develop a new hypothesis that needs to be carefully examined in future studies.

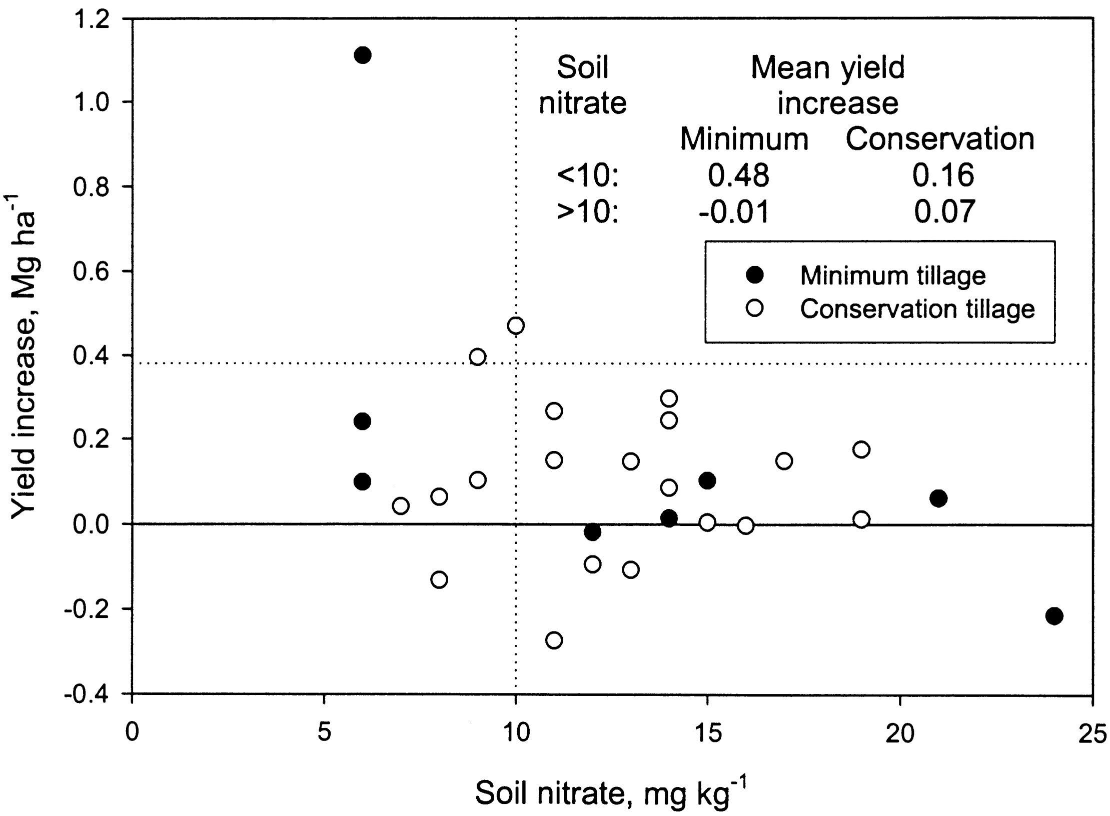

Fig. 6. Relationships among tillage practices, soil nitrate concentrations, and yield increases to the extra N applied in June.

Stalk nitrate concentrations

Figure 7 shows the relationship between end-of-season stalk nitrate concentrations with and without extra N across all sites where the extra fertilizer was applied in June, and Table 6 shows the mean values and ranges. The y-intercept showed that the extra fertilizer N increased cornstalk nitrate concentrations by an average of 0.42 g kg^{-1}. The upward shift in the regression line from the one-to-one line presents evidence that the plants took up some of the extra N, although it is not possible to quantify the amount taken up from our measurements. Because luxury uptake of nitrate occurs in cornstalks (Blackmer and Mallarino, 1996), addition of extra fertilizer should be expected to increase stalk nitrate concentration even in situations where supplies of N are adequate to maximize yields.

It is noteworthy that three sites testing <0.3 g kg^{-1} without the extra N also tested <0.3 g kg^{-1} with the extra N. Because such low stalk nitrate concentrations indicate high likelihood that extra fertilizer N will increase yields, the lack of yield increase suggests a high likelihood that the extra fertilizer N was not available for uptake by the plant. It is possible that the fertilizer N remained in a dry layer of surface soil and never moved deep enough to be taken up by plant roots. Soil nitrate data presented (Fig. 6) showed that these sites had low concentrations of nitrate in late spring. Measurements indicating low concentrations of soil nitrate in the spring and low concentrations of nitrate in stalks at the end of the season provide compelling evidence that the additional applications of fertilizer did not become available to the plant. Evidence that the fertilizer N was not available to plants may help explain apparent failures of the soil nitrate test to predict yield increase to added N in other studies.

Careful examination of the relationship shown in Fig. 7 suggests that two different types of relationships may exist; one where the extra fertilizer was available to plants and one where it was not. When this distinction is made, all of the minimum-tillage fields fell in the first category. This observation suggests that the effects of tillage may be caused by greater effectiveness of the fertilizer in the minimum-tillage fields rather than greater losses of fertilizer N applied earlier. A possible explanation is that tillage disrupted the continuity of pores to the surface and thereby helped to isolate nitrate in an air-dried layer of surface soil.

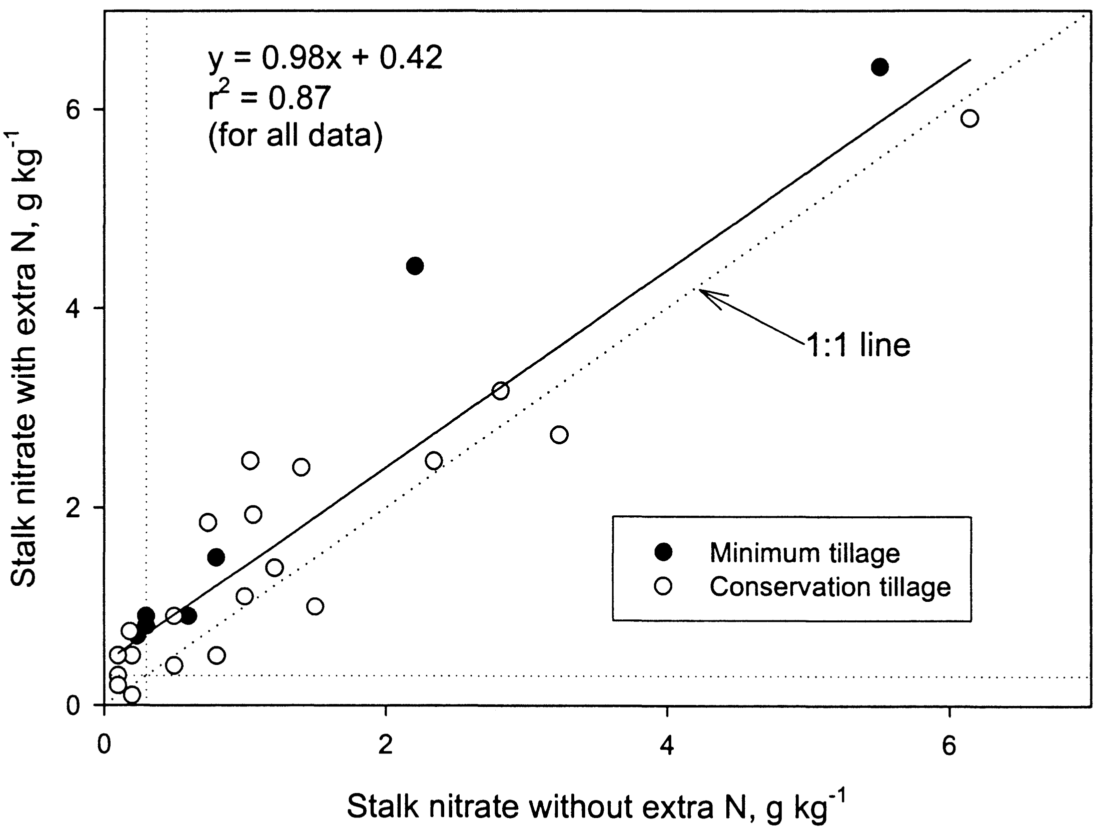

Fig. 7. Relationship between end-of-season stalk nitrate concentrations with and without extra N at sites where the extra fertilizer was applied in June.

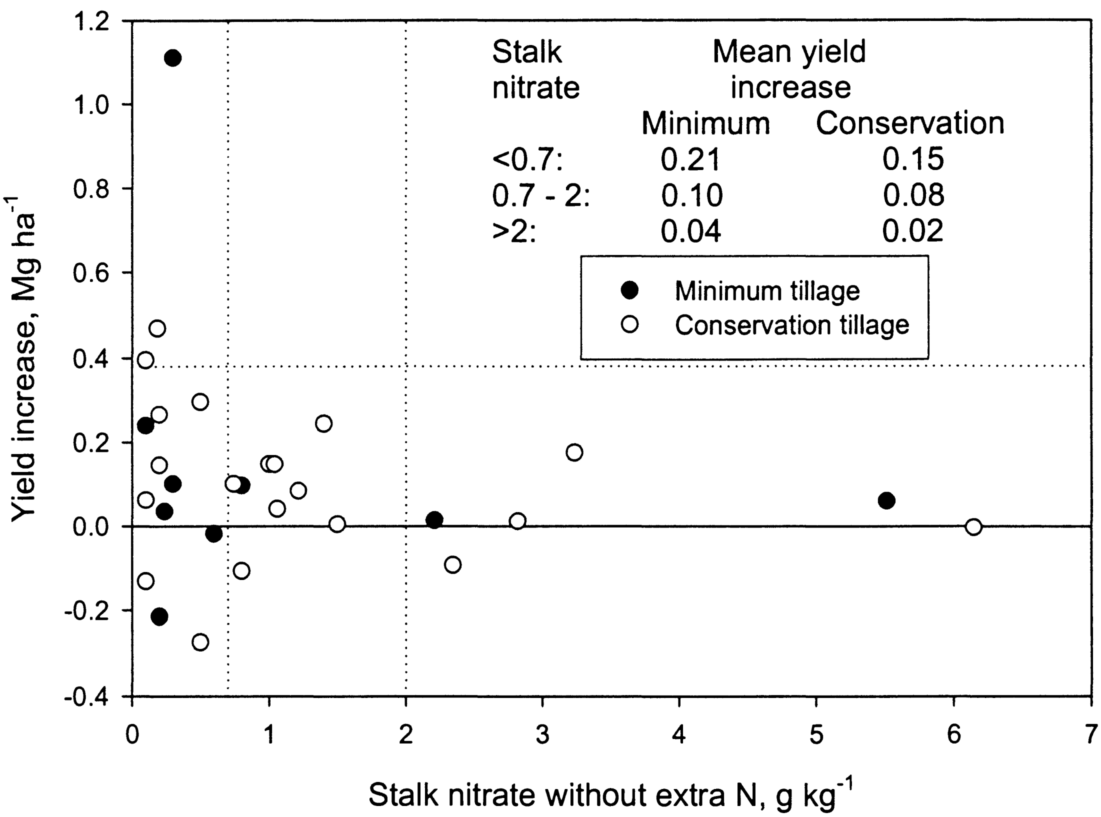

Fig. 8. Relationship between stalk nitrate concentrations and yield increases to extra N applied in June.

Figure 8 shows relationships between stalk nitrate concentrations at the end of the season on plots without the extra N and yield increases resulting from extra N. As should be expected, the yield increases tended to decrease with increasing stalk nitrate concentration in plots without the extra N. The yield increases were too small to be of economic importance when stalk nitrate concentrations were >0.7 g kg^{-1}. The results of the stalk test show good agreement with the soil test because each test correctly identified the sites where yield responses were significant enough to justify the expense of the extra N. The cornstalk test also showed that the percentage of the fields deficient of N without the extra N was greater for fields with minimal tillage than fields with conservation tillage.

The mean yield increases due to the extra N were not great enough to pay for the extra N even in fields where cornstalk nitrate concentrations were <0.7 without the extra N. This observation could be taken as evidence that the stalk test is not as useful as the soil test for classifying fields with respect to need for extra N. Unlike the soil test, however, use of the stalk test provided compelling evidence that lack of yield increase at some sites should be attributed to lack of efficacy of fertilization rather than lack of need for fertilization.

Extra N Applied after June

The mean yields of corn grain at 32 sites were 11.28 Mg ha^{-1} without the extra N and 11.29 Mg ha^{-1} with the extra N applied after June (Table 7). The mean yield increase of 0.01 Mg ha^{-1} was too small to pay for the additional fertilizer and application, so it must be concluded that it was not profitable to apply the extra N across all sites.

Yield increases resulting from the extra N ranged from 0.71 to -0.63 Mg ha^{-1} and had a mean of 0.01 Mg ha^{-1}. The yield increases were large enough to justify the normal expense of the fertilizer and application (i.e., >0.38 Mg ha^{-1}) at 2 of the sites. Only at 1 site was the yield increase great enough to give a two-fold economic return to fertilization. The results suggest, therefore, that it is not wise to apply

Table 7. Yields of corn grain with and without extra N applied after June.

Site	Yield: With Extra N	Yield: Without Extra N	Yield Increase	LSD	p-value
	---- Mg ha^{-1} ----				
1	11.31	10.60	0.71	0.62	0.03
2	6.18	5.56	0.62	0.24	0.00
3	11.68	11.44	0.24	0.66	0.42
4	12.74	12.60	0.15	0.33	0.35
5	11.25	11.11	0.14	0.60	0.58
6	11.18	11.04	0.14	0.21	0.15
7	10.93	10.79	0.14	0.56	0.56
8	12.95	12.82	0.14	0.30	0.30
9	15.28	15.16	0.12	1.12	0.76
10	12.56	12.45	0.11	0.24	0.15
11	13.65	13.57	0.09	1.94	0.89
12	10.55	10.47	0.08	0.22	0.46
13	12.04	11.99	0.05	0.36	0.72
14	11.27	11.22	0.04	0.23	0.60
15	11.04	11.05	-0.01	0.37	0.96
16	10.44	10.48	-0.04	0.19	0.67
17	11.66	11.70	-0.04	0.60	0.85
18	10.77	10.82	-0.05	0.15	0.50
19	11.67	11.73	-0.06	0.24	0.56
20	12.98	13.04	-0.07	0.17	0.41
21	9.04	9.12	-0.08	0.26	0.50
22	10.41	10.49	-0.09	0.35	0.37
23	9.94	10.03	-0.10	0.26	0.37
24	12.72	12.83	-0.10	0.34	0.48
25	11.37	11.48	-0.11	0.79	0.75
26	11.77	11.91	-0.14	0.39	0.40
27	10.38	10.53	-0.15	0.48	0.53
28	11.69	11.86	-0.17	0.52	0.37
29	10.50	10.67	-0.17	0.46	0.35
30	11.55	11.82	-0.27	0.42	0.13
31	9.94	10.23	-0.30	0.30	0.05
32	9.84	10.48	-0.63	0.13	0.00
Mean	11.29	11.28	0.01		

fertilizer unless there is clear evidence of need for extra N.

Figure 9 shows relationships between cornstalk nitrate concentrations at the end of the season and yield increases resulting from extra N. The mean concentrations for the cornstalk nitrate test and range are shown in Table 8. As should be expected, the yield increases tended to decrease with increasing stalk nitrate concentration and were too small to be of economic importance at 0.7 g kg^{-1}.

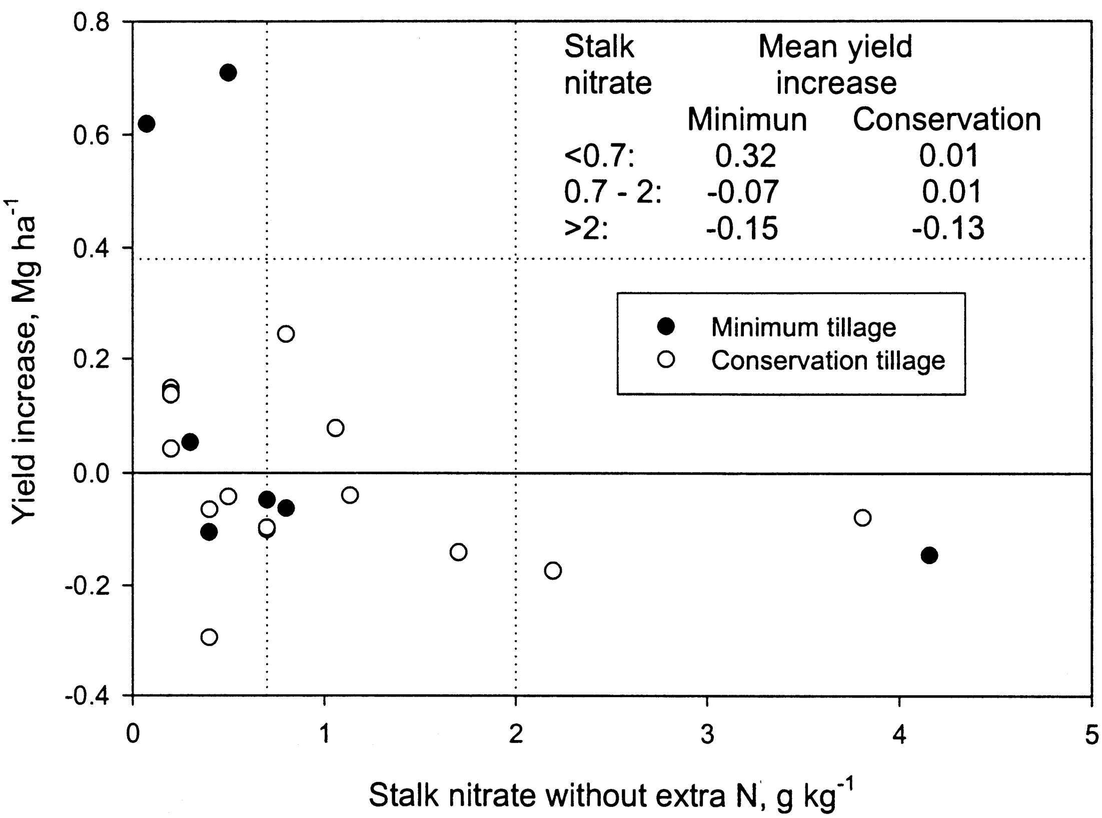

Fig. 9. Relationship between stalk nitrate concentrations and yield increases to extra N applied after June.

Table 8. Soil and stalk nitrate concentrations for sites applied after June.

			Stalk Nitrate			
	Soil Nitrate		With Extra N		Without Extra N	
Site	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
	------------ mg N kg^{-1} ------------		------------ g N kg^{-1} ------------			
1	6	3 - 9	0.5	0.2 - 0.9	0.5	0.2 - 1.2
2	--	----	0.4	0.3 - 0.7	0.1	0.0 - 0.1
3	11	7 - 16	1.1	0.6 - 1.3	0.8	0.4 - 1.2
4	11	8 - 15	0.4	0.2 - 0.9	0.2	0.1 - 0.3
5	18	12 - 26	--	----	--	----
6	9	6 - 13	0.4	0.0 - 1.1	0.2	0.0 - 0.6
7	12	7 - 17	--	--	--	----
8	13	6 - 19	0.4	0.2 - 0.9	0.2	0.1 - 0.5
9	17	12 - 26	--	----	--	----
10	21	16 - 29	--	----	--	----
11	16	12 - 24	--	----	--	----
12	7	5 - 8	1.9	0.6 - 2.6	1.1	0.2 - 1.5
13	6	4 - 10	0.4	0.2 - 0.6	0.3	0.1 - 0.6
14	8	4 - 12	0.6	0.3 - 1.2	0.2	0.0 - 0.6
15	14	9 - 18	--	----	--	----
16	--	----	1.3	0.7 - 1.9	1.1	0.3 - 1.6
17	14	5 - 28	0.7	0.4 – 1.0	0.5	0.2 - 0.9
18	15	13 - 18	0.7	0.2 - 1.3	0.7	0.1 - 1.0
19	12	9 - 14	0.7	0.5 - 0.7	0.8	0.4 - 1.1
20	13	8 - 21	0.5	0.2 – 1.0	0.4	0.1 - 0.7
21	--	----	3.8	2.0 - 5.3	3.8	2.5 - 5.4
22	14	6 - 20	--	----	--	----
23	11	7 - 15	0.8	0.5 - 1.1	0.7	0.5 - 1.0
24	6	4 - 10	0.5	0.3 - 0.6	0.7	0.2 - 1.9
25	17	13 - 22	0.6	0.2 - 1.3	0.4	0.0 - 0.9
26	14	8 - 19	1.7	1.3 - 1.9	1.7	0.6 - 2.7
27	--	----	4.6	3.0 - 5.6	4.2	2.8 - 5.1
28	15	9 - 23	--	----	--	----
29	--	----	1.5	0.8 - 2.6	2.2	0.0 - 3.5
30	10	6 - 17	--	----	--	----
31	8	5 - 12	1.0	0.1 - 2.2	0.4	0.1 - 1.0
32	19	12 - 22	--	----	--	----
Mean	12		1.1		1.0	

Figure 10 shows the relationship between stalk nitrate concentrations with and without extra N. Some upward shift in the regression line from the one-to-one line occurred, but this upward shift was less than observed than when fertilizer was applied earlier. This observation suggests that N applied later in the season was less available to plants than N applied earlier in the season. Although it was expected that the later applied N would be less available, the effect of the extra N was less than expected.

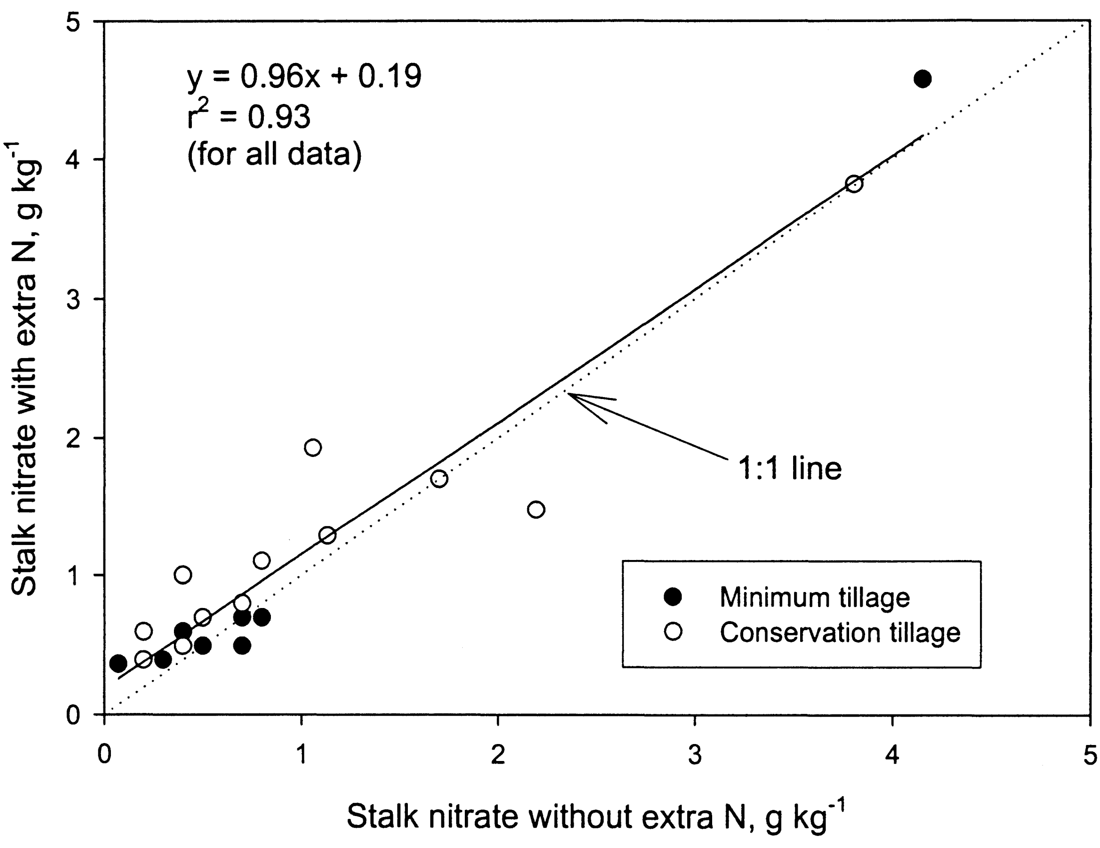

Fig. 10. Relationship between end-of-season stalk nitrate concentrations with and without extra N at sites where the extra fertilizer was applied after June.

CONCLUSIONS

The results of this study provide compelling evidence that in-season applications of fertilizer N in addition to that normally applied by producers are not likely to be profitable unless there is compelling evidence of a deficiency of N. A primary reason is that most producers normally apply enough extra fertilizer (i.e., insurance N) to compensate for losses of N that occur on most years. Even when a deficiency of N is present, such applications of fertilizer may not be an effective solution because there often is inadequate rainfall to move the fertilizer N into the active rooting zone.

The idea of in-season fertilization to correct deficiencies should not be abandoned because responses to in-season fertilization have been observed and should be expected under some conditions. Refinement of this technique may be important as producers reduce N rates for economic and (or) environmental reasons. It is clear, however, that such fertilization is not likely to be profitable without better methods of predicting where responses are likely to occur.

The results demonstrate the great complexity of the task of evaluating and improving N management practices. Evaluations must be based on measurements of yield increases to fertilizer treatments because fertilizers are applied to increase yields and profits. The yield responses observed, however, are greatly influenced by interactions of weather and management practices. These factors simultaneously influence the amount of N supplied by the soil, the movement of fertilizer N into and out of the active rooting system, and the potential for growth and plant demand for N.

Soil testing for nitrate in late spring can explain some of the variability among sites in plant responses to fertilizer N, but can explain only part of the variability. Cornstalk testing at the end of the season can also explain some of this variability, but it can explain only part of this variability. Simply measuring the variability in yield response does not explain why the variability occurs. Only through the simultaneous use of these tools will it be possible to improve the capability to predict yield responses before fertilizers are applied.

Yield monitors and on-farm strip-plot trials should greatly enhance efforts to evaluate and improve N-management practices because relatively large numbers of trials can be conducted at relatively little cost. The large number of trials makes it possible to address the complex interactions of weather and management practices that could not be addressed in the past.

The ability to measure yield responses at many sites makes it possible to collect enough data to adjust soil-test interpretations for site-specific conditions. This advantage of using yield monitors should not be overlooked because only soil testing has the ability to detect problems early enough to add more fertilizer. Any evidence that interactions of weather and management have important effects on the movement of fertilizer N into and out of the active rooting zone, therefore, should be considered evidence that the yield monitors and on-farm strip trials should enhance our ability to evaluate and improve N management practices.

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